Modeling and Control of Grid Connected Variable Speed PMSG Based Wind Energy System

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Abstract

In recent years, The advancement of power electronic technology, novel control strategies and new circuit topologies, the grid connected small wind turbine industry is primarily dominated by the permanent magnet synchronous generators (PMSG) have increasingly drawn interests to wind turbine manufactures. This paper presents modeling and control strategy for the grid connected PMSG-based wind turbine systems, where PMSG is used as a variable speed generator. The two mass drive train models is established for coupling the wind turbine and generator , pitch angle control at high wind speed, an LC filter is used at both side of grid side converter for desired power quality. The control scheme is developed for grid side converter to get regulated voltage at grid side. The simulation model is tested in MATLAB/SIMULINK environment.

Keywords: Drive train, grid side converter (or inverter), LC filter, PMSG, wind turbine.

1. Introduction

There are various types of wind power systems, some of which are connected to power system grid and some independent of the power grid. Many wind power sources have been installed in isolated islands and remote villages. However, since these wind power systems are highly dependent on the wind, it is necessary to link them with the power grid so that they can continuously provide electric power to customers, which is a big incentive for both customers and utility companies[1][2].

In the recent years, wind energy conversion systems have become a focal point in the research of renewable energy sources. This is in no small part due to the rapid advances in the size of wind generators as well as the development of power electronics and their applicability in wind energy extraction. For isolated settlements located far from a utility grid, one practical approach to self-sufficient power generation involves using a wind turbine with battery storage to create a stand-alone system [3]. The use of permanent magnet machines has become attractive for use in wind turbines because now days the available permanent magnet materials have high coercive field strength and temperature resistance, and are price competitive. In addition, the required power electronic converters for output power control have undergone a major evolution.

Modern, high performance PWM converter provides desired power factor and low harmonics distortion in system

2. Wind Turbine Model

The wind turbine converts energy of wind flow into mechanical energy. The turbine shaft drives the generator rotor through drive train. The mechanical power output from the wind turbine is

$$P_m = \tfrac{1}{2}\rho A C_p V_w^3 \quad (1)$$

Where ρ is the air density, A is the sweep area of the turbine blades, V_w is wind speed, C_p is the Aerodynamic power coefficient which is a function of the pitch angle β and the tip speed ratio λ. Since ρ and A are constant parameters, the wind turbine can produce maximum power under a certain wind speed only when the turbine operates at the maximum C_p. A generic equation is used to express C_p. This equation, based on the turbine characteristics of, is given by

$$C_p(\lambda,\beta) = C_1\left(\tfrac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \quad (2)$$

With

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3)$$

β is blade pitch angle, and λ is defined by

$$\lambda_m = \frac{\omega_m R}{V_w} \quad (4)$$

In (4), ω_m is the turbine angular velocity and R is the turbine radius. In small wind turbine generation systems, β is rarely changed. Where $c_1 = 0.5716, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21$ and $c_6 = 0.0068$ fig. 1 shows the $C_p - \lambda$ curve described by (2) for different pitch angle of β .The maximum value of C_p (C_{pmax} =0.48) is achieved β =0 degree and for λ =8.1.This particular value of λ is defined as nominal value (λ_{nom}).

3. PMSG Modeling

Permanent magnet have been extensively used to replace the excitation winding in synchronous machines with the well-known advantages of simple rotor design without field windings, slip-rings and excitation system.

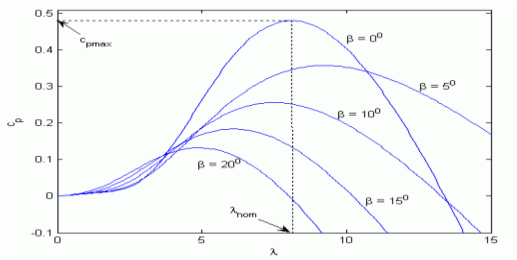

Fig. 1. Cp-λ curve.

Hence, avoiding heat dissipation in the rotor winding and providing higher overall efficiency. Recently the PMSG is gaining lot of attention for WECS due to compact size, higher power density, reduced losses, high reliability and robustness. Moreover there is a need of low speed gearless generator, especially for off-shore wind applications, where the geared doubly fed induction generator or induction generator will require regular maintenance due to tearing-wearing in brushes and gear box. Both the brushes and gear box can be eliminated from WECS by using directly coupled low speed generators. Further, the elimination of gear box can increase the efficiency of wind turbine by 10% [4][5]. The low speed PMSG requires:

a. Higher number of poles to get suitable frequency at low speed and
b. Big rotor diameter for the high wind turbine torque.

In case of asynchronous generators having large no. of poles, the magnetizing current is very high due to their low magnetizing reactance. Hence, for low speed operation, PMSG with large number of poles are highly beneficial. The dynamic model of PMSG can be represented in rotating reference frame with the help of following equations.

$$V_q = -R_s i_q - L_q \frac{di_q}{dt} - \omega_r L_d i_d - \omega_r \lambda_m \quad (5)$$

$$V_d = -R_s i_d - L_d \frac{di_d}{dt} - \omega_r L_q i_q \quad (6)$$

The expression for electromagnetic torque in the rotor can be written as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\left(L_d - L_q\right)i_q i_d - \lambda_m i_q\right] \quad (7)$$

In case of cylindrical rotor, the $L_d \approx L_q$ and hence the above equation reduces to

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_m i_q \quad (8)$$

4. Drive Train Model

Drive train as the mechanical system of a wind turbine consists turbine, generator and gear box. The major sources of inertia of this system lie in the turbine and generator. The tooth wheels of the gearbox contribute only a relatively small fraction. For this reason, the inertia of the gear is often neglected and only the transformation ratio of the gear system is included, but in this modeling gear ratio is taken to unity. Thus, drive train is modeled as a two mass model, with a connecting shaft, and with all inertia and shaft elements as indicated in fig. 2.

The dynamic equations of drive train written on the generator side are

$$2H_{tur}\frac{d\omega_{tur}}{dt} = T_{tur} - K_s\theta_s - D_s\left(\omega_{tur} - \omega_{gen}\right) \quad (9)$$

$$2H_{gen}\frac{d\omega_{gen}}{dt} = K_s\theta_s - T_{gen} + D_s\left(\omega_{tur} - \omega_{gen}\right) \quad (10)$$

$$\frac{d\theta_s}{dt} = \omega_{tur} - \omega_{gen} \quad (11)$$

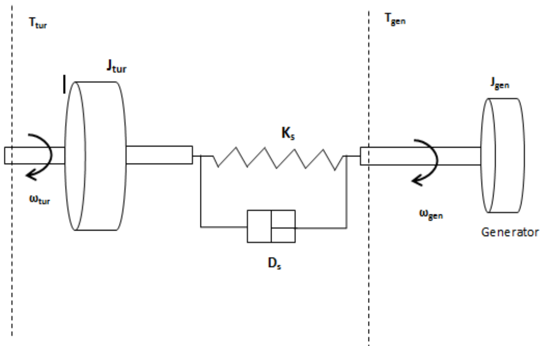

Fig. 2. Two mass drive train model

Where

T_{tur} - Wind turbine torque

T_{gen} - Generator torque

H_{tur} -Wind turbine moment of inertia constant

H_{gen} - Generator rotor moment of inertia constant

ω_{tur} - Wind turbine speed

ω_{gen} - Generator speed

K_s -Shaft stiffness

D_s - Damping coefficient.

5. Pitch angle Control

The pitch angle controller is active only in high wind speeds, normally. In such circumstances, the rotor speed can no longer be controlled by increasing the generated power, as this would lead to overloading the generator and/or the converter. Therefore the blade pitch angle is changed in order to limit the aerodynamic efficiency of the rotor. This prevents the rotor speed becoming too high. Unbalance power between output and wind energy input will increase the rotor speed of the generator. The pitch angle should be changed, to balance the electrical and mechanical power. After the fault, pitch angle will be change back to normal operation. Pitch angle controller model is shown as fig. 3. PI controller is used for pitch angle controller. The output of PI controller is the speed of pitch angle, it always limited up to 5°/s for normal operation. In this model, the actuator and mechanical system is equivalent to an inertial link. It should be taken into account that the pitch angle cannot be changed immediately, because of the size of the rotor blades.

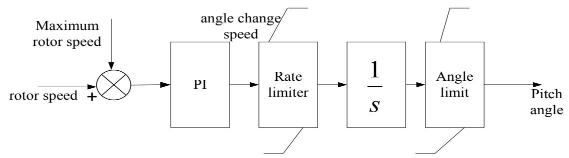

Fig. 3. Pitch Angle Controller Model

6. Power Electronics Interface

The power electronic plays an important role in the wind energy conversion systems. As the wind turbine operates at variable speed according to available wind velocity, the voltage generated is of variable magnitude and frequency. Therefore the power generated is needed to be processed before feeding it to grid or isolated network. Several types of power electronic interfaces have been investigated for variable speed wind turbines [6][7]. The proposed system consists of two back to back converters decoupled by a dc-link. Generator side converter is uncontrolled rectifier. The grid side converter has been realized by using six IGBT switches for each converter. Since PMSG is connected to grid through AC/DC/AC system, only active power of PMSG can be transferred to grid and exchange of reactive power cannot take place due to presence of dc-link. To make the dc link voltage ripple free a LC filter is connected after AC/DC Rectifier. The control scheme is developed for grid side converter.

7. Control of grid side converter

The control of grid side converter is to regulate the output voltage of dc/ac converter shown in fig. 4. The LC filter output voltage is measured and transformed into d-q variable and compared with reference voltage which is taken as one p.u. whole of the control scheme for grid side converter is developed through d-q transformation technique.

Simulink diagram of voltage regulator is shown in fig. 5. The six-pulses to dc/ac converter is given through discrete PWM generator. PWM generator takes the input from output of the d-q to abc conversion block. PWM converter has capability to absorb and deliver the reactive power for the requirement of voltage regulation.LC filter along with grid side PWM converter regulate the voltage of grid side with low harmonic distortion. Frequency of PWM generator is taken between 5 to 10Kz.

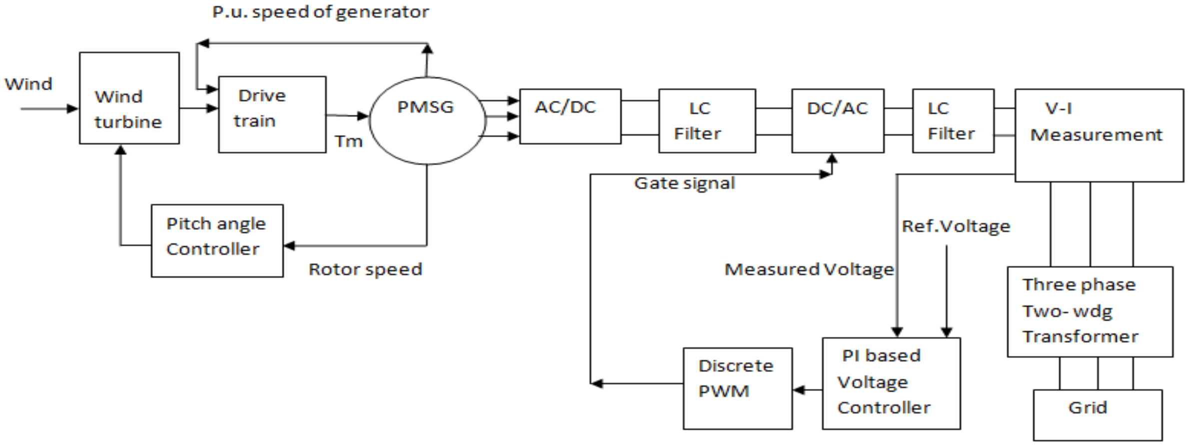

Fig. 4. Block diagram of grid connected PMSG based wind turbine system

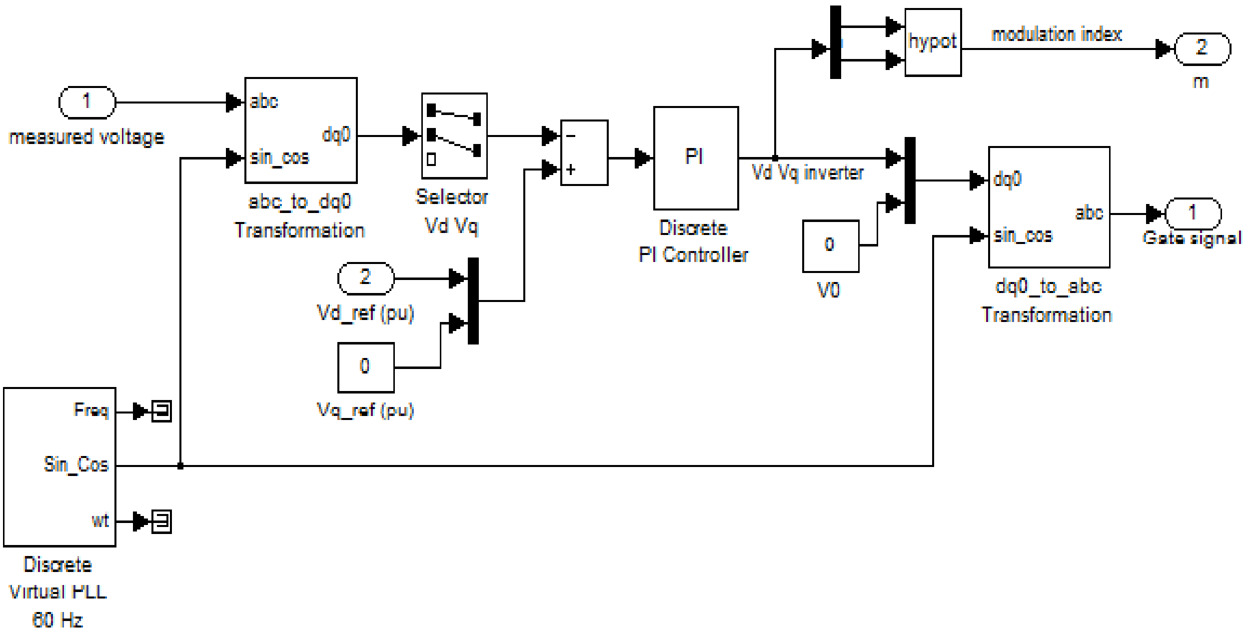

Fig. 5. Simulink diagram of voltage control for grid side converter

8. Simulation results

The system described above was simulated using matlab Simulink environment. Wind speed profile is in stepped form. Although real wind does not occur with such abrupt slopes, a series of steps is a standard testing signal which permits a clear interpretation of the system behavior Fig. 6 shows rotor speed and pitch angle control. Pitch angle control comes into picture at higher wind speed, when the generator speed increases above base speed due to increase of wind speed.

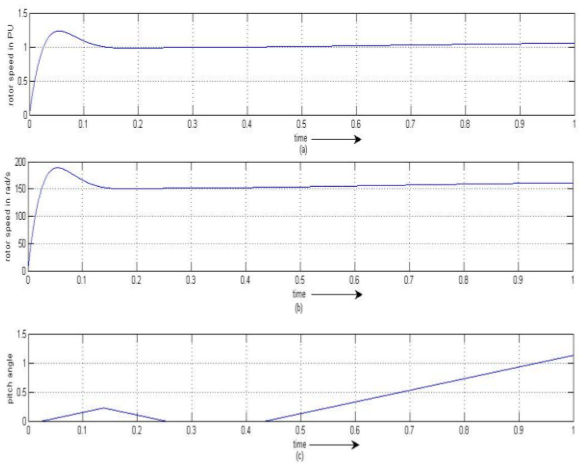

Fig. 6. (a) rotor speed of generator in p.u. (b) rotor speed of generator in rad/s and (c) pitch angle.

Fig. 7. (a) and (b) shows instantaneous output voltage and current of PMSG. Fig. 7 (c) and (d) shows phase to phase rms value of voltage and current of PMSG. The output power of PMSG is shown in figure (e). The maximum power output of wind turbine at base speed is 0.8 times of nominal mechanical power of turbine, which is shown in fig. 8.

Fig. 9. (a) and (b) shows rectifier voltage and inverter output voltage respectively . The THD in inverter output voltage around 64%, which contain a large number of harmonics. A LC filters after inverter output is connected to suppress the harmonics. Filter output voltage contain only 1.4% THD value, which is shown in fig. 9 (c).

9. Conclusion

This paper has proposed modeling and control of grid connected wind energy system using Matlab/Simulink. The modeled system including all subsystems is

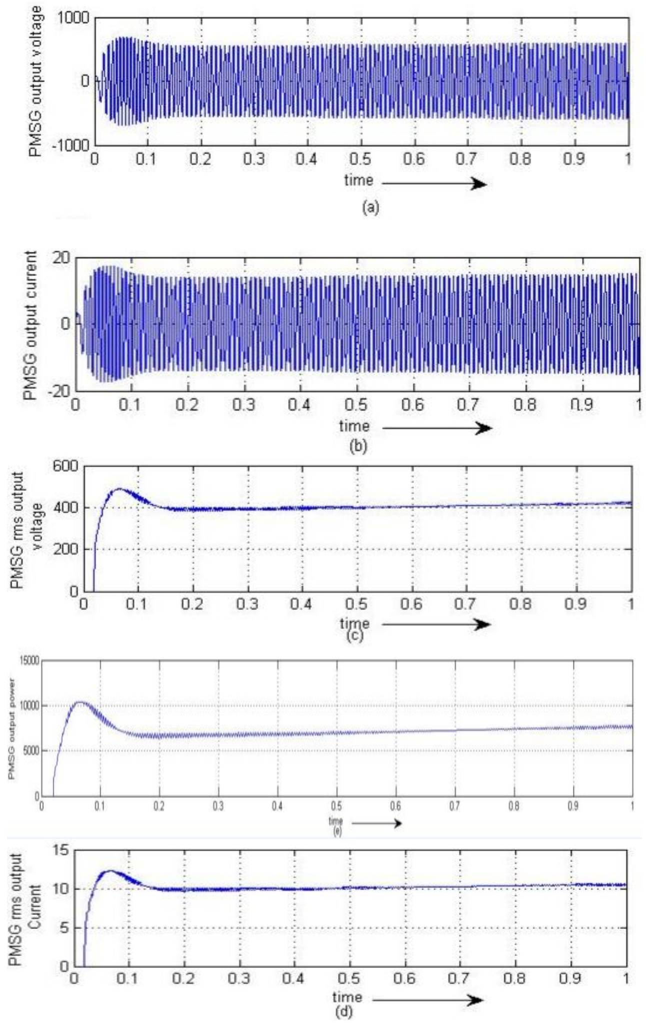

Fig. 7. (a) Instantaneous output voltage of PMSG.(b) instantaneous output current of PMSG(c) rms output voltage of PMSG.(d) rms output current of PMSG and (e) generator output power

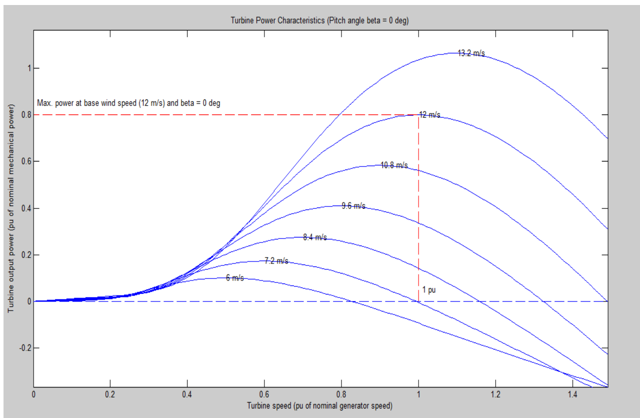

Fig. 8. p.u. turbine output power versues turbine speed

characterized and analyzed for validation. In the modeling of drive train neglecting the gear ratio and it reduces the losses in the system. Pitch angle control has precisely implemented to control mechanical power generated by the turbine. Control algorithm for grid side converter along with LC filter is developed to regulate the voltage at grid side with desired power quality.

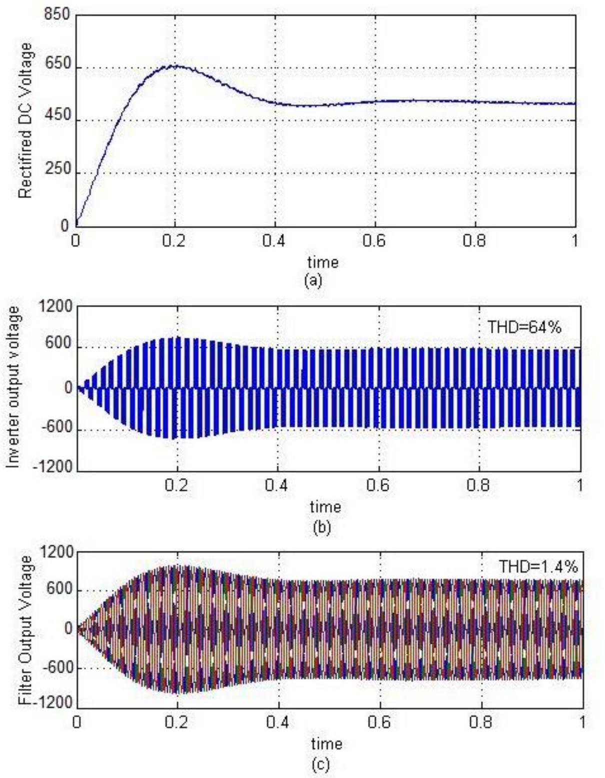

Fig. 9. (a) Rectified dc voltage .(b) inverter output voltage and (c) filter output voltage

Table 1. Parameters of PMSG

Parameters	Values
Rated power of generator	8.5 kw
Grid voltage and frequency	575V,60Hz
Load at grid side	6.8 kw
Base speed	152.5 rad/s
Ld stator d-axis inductance	0.0082H
Lq stator q-axis inductance	0.0082H
Permanent magnet flux	0.482Wb
Number of pole pairs	5

Table 2. Parameters of Turbine

Parameters	Values
ρ air density	1.08kg/m2
Base wind speed	12m/s
Inertia constant(p.u.)	4

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